Abstract: Mass production in microelectronics and solar cell industry poses a problem of creating cheap and fast sensors being able to perform on-line quality testing of semiconductor wafers and bulk dielectric components in fab conditions. A challenging task is to determine areas of residual stress and associated high density of dislocation and microcracks in large format (up to 30 x 30 mm) but ultra-thin (less than 0.32 mm) polycrystalline Si wafers. In addition to microwave and ultrasound inspection methods, which only partially address the problem, the optical polarization heterodyne interferometry seems to be a promising solution. The method exploits the fact that the residual stress within silica wafer induces the anisotropy (birefringence) of the optical properties of the material due to the photo-elastic effect. The birefringence, in turn, can be evaluated by registering the phase difference between two orthogonally polarized waves passing through or reflecting off the wafer. Recently, the feasibility of polariscopy method was discussed for stress detection in Si, which exploits similar physical principles. These approaches determine depolarization analyzing the beam intensity for different polarization orientation. However, especially solar cell wafers have rough surfaces and hence a polarization dependent modification of the beam intensity will be observed. Hence the birefringence information will be masked by the surface effect. In this contribution we propose an alternative implementation of the polarization interferometry, where the birefringence phase shift of two beams with a polarization perpendicular to each other is measured directly independent on the intensity of both beams. The developed testing system provides a number of advantages over the polariscopy, in particular, the absence of mechanical movement of components, larger field of view, better accuracy for depolarizing non-polished wafers, and much higher operating rates. With the help of an industrial demonstrator it was able to analyse the mechanical stress state of a solar cell of 160x160 mm² in transmission as well as in reflection in less than 1 s with a resolution less than 80 µm.

Keywords: Solar Cell Inspection, Stress and Cracks, Optical Birefringence, Heterodyne Polarization Interferometer, Industrial Demonstrator

1. INTRODUCTION

In the photovoltaic industry there is an urgent demand for a reliable and fast nondestructive method of detection of residual stress [1] and micro-cracks in polycrystalline Si wafers used for mass production of solar cell panels. The presence of the residuum stress is inevitable in large-format and ultrathin Si wafers due to the inherent thermal gradients of the technology of growing of ingots and the mechanical impact of the subsequent slicing. High level of non-controllable stress results in a large density of dislocations, which potentially may evolve into micro-cracks and lead to unexpected breakage of the whole wafer. A micro-crack may develop at any of numerous wafer processing steps, like polishing, metallization, or etching, therefore it is important to provide earlier detection of critical areas to prevent a leakage of defective wafers into the final product of solar cell panels and to minimize the manufacturing costs by avoiding unnecessary technological operations. Also, overall monitoring of the production sequence is preferable to ensure the integrity of solar cell panels, their high working efficiency and durability. The inspection method is demanded for testing non-destructively large-format and ultrathin (300 x 300 x 0.15 mm) wafers in less than 1 second in order to
detect micro-cracks and critical residual stress locations. The method is to be integrated into the production line to reject cracked wafers from further processing. The inspection has to be carried out at any stage of the manufacturing process and needed to operate reliably in the fabrication environment, i.e., in the presence of vibrations, turbulence and temperature variations. Capabilities to characterization of different types of wafers, mono and polycrystalline ones, with polished, rough and metalized surfaces are required.

Up to now no reliable solution exists, which falls within the expected specification. Visual inspection or machine vision systems could provide only less than 50% of detection probability. Among the most appropriate methods one could use in-situ are imaging with millimeter waves (MWI) [2], measurement of Resonance Ultrasonic Vibrations (RUV) [3] and near-infrared polariscopy. The MWI lacks of enough spatial resolution. The RUV method is rather accurate, however, is not so fast (~2s per wafer), it is not able of resolving defects locally (a resonant frequency of a whole wafer is determined), fails to discover micro-cracks smaller than 1 mm, and requires specific calibration for each type of wafers and their dimensions. The known implementation of the IR polariscopy [4] is slow as it uses ordinary non-laser sources and exploits rotating polarizing elements. Also, it is problematic to cover large wafer formats due to limited input apertures of polarizing elements. However, despite of technical imperfection recently it has been demonstrated that the infrared photo-elastic polariscopy is a quite powerful technique to measure residual stress and identify various types of bulk micro-defects in polycrystalline Si-wafers [5-7].

2. PROPOSED SOLUTION

We have proposed a relevant solution, which fully matches the requirements of photovoltaic manufacturers and has no mentioned shortcomings. It is a polarization-sensitive IR interferoscopy technique, which is capable to detect and visualize the stress-induced optical birefringence of a sample. The optical birefringence is directly linked to the stress by the photo-elastic effect and becomes apparent through the difference in the speed of propagation of ordinary and extra-ordinary polarized beams of laser radiation passing through or reflecting off the wafer – see Figure 1. The difference of the light speed or the optical path can be measured very accurately with the interferometric approach. In such a way the induced stress can be visualized as it is shown in Figure 2.

![Figure 1: Stress-induced birefringence. Ordinary and extra-ordinary polarized beams suffer a phase shift δ passing through the stressed.](image)

![Figure 2: Visualization of stress-induced birefringence in a plastic sheet with imposed tension.](image)

In the lab an experimental set up was developed, Figure 3, and tested for later application for Si-wafer control. A collimated beam of IR laser, radiating at the edge of the transparency band of the Si, enters a polarization interferometer with variable optical path, which splits the radiation into two orthogonally polarized beams and set for the beams a predefined optical path delay δ. Leaving the interferometer the beams are expanded to cover required wafer area and propagate towards a sample along a common track. Transmitting through a sample the two beams acquire additional path
delay due to the sample birefringence and interfere on the analyzing polarizer at the entrance of a CMOS camera producing an intensity-modulated pattern. This interferogram has a sinusoidal form obtained by step like varying the initial phase delay $\delta$ by the polarization interferometer. The phase shift $\phi_n$ inherent to the sample, i.e. the stress in the Si-wafer corresponding to the n-th pixel, can be extracted from the captured interferograms, which are processed by the software to generate maps of the induced-birefringence (stress maps). These maps can be used for determining a permissible level of residual stress or further transfers to the image recognition software for precise localization of critical areas or micro-cracks.

Figure 3: Principal optical setup for a stress analyzer in transmission. Above: 1 – IR laser, 2 – polarizing delay line (phase retarder), 3 – expanding optics, 4 – wafer, 5 – imaging optics, 6 – analyzer, 7 – CMOS camera. Below: Technical realization of the phase stepping polarization interferometer

3. RESULTS AND DISCUSSIONS

Several types of samples, including mono and polycrystalline Si wafers and solar cells with metallized back surface have been measured. For cross reference some of the samples containing defects were inspected by highly resolved IR microscopy as well as by visual inspection. It was noted that micro-cracks which propagates to the outer edge of the wafer, as well as aged micro-cracks (originated more than several days before the measurement was made) are not exhibit high value of stress which has been eventually released. Therefore such defects hardly can be detected by the presented method. As for the fresh cracks, especially if they have their ends within the interior of the wafer, the stress is
strong enough to be detected. Below in Figure 4 some typical images of defective wafers captured by the tool are presented.

![Figure 4: Typical IR images of Si wafers obtained in transmission; a) – ordinary image; b-c) stress maps at the presence of cracks](image)

In addition to the transmission layout the device can be modified for the stress measurement in reflection, which is needed to evaluate the quality and integrity of metallized solar cells. In this case the laser radiation passes through the bulk of the wafer and reflected from the metallized back towards the camera. Except of the cracks some signal is generated by the metal electrodes covering the wafer, however, they easily can be subtracted by math processing of the images and do not prevent crack detection.

![Fig. 4. Typical IR images of Si wafers obtained in reflection; a) – ordinary image; b-c) stress maps at the presence of cracks](image)

Compared to known implementation of the IR polarimetry method, which utilizes the same working principle of measuring the stress-induced birefringence, the IR polarization interferoscopy is unique for several features. 1) Contrary to using rotating polarizing elements we introduced an ultrafast delay line, which in combination with a laser source, enables to boost the operating rates of the device by several orders without compromising the accuracy. Also, we managed to avoid using electro-optical or acoustic-optical modulators, which performance degrades significantly in the presence of temperature variation. 2) Common path interferometer setup minimizes the influence of vibrations and the air turbulence. 3) Innovative beam expanding system eliminates the need for large aperture polarizers and permits to test large format wafers instantly. 4) Either CMOS or CCD cameras are exploited for the IR detection as an alternative to highly-sensitive but extremely costly IR GaAs array detectors. Lack of sensitivity of the detector is compensated by using a laser, which ensures short exposure times, bright illumination and excellent signal-to-noise ratio through the large field of view, and required high spatial resolution.
The solution is characterized by the ultimate accuracy and sensitivity, high noise immunity, fast measurement time, capability of testing large field of view, flexible adaptation to a wafer type of interest and low costs. It can be used both for in-situ metrology and research purposes.

For in-situ implementation the measurement device has to be installed into the production line. Wafers are transported by the conveyor in front of the tool and sequentially exposed by the radiation. Interferograms are captured and transferred to the input of a processor, which recognizes a defective wafer based on the results of the data analysis. The processor provides a pass/fail signal to remove wafers having either critical level of residual stress or developed micro-cracks from the conveyor, which is realized by a robotic arm. Using the method in reflection, wafer control is able at each stage of the photovoltaic wafer process.

4. CONCLUSIONS

The feasibility of the full-field imaging of stress-induced birefringence in large-format ultra thin poly Si wafers has been demonstrated in transmitted and reflected light. The method enables to reach the necessary precision for unambiguous detection of cracks and highly stressed areas. A high reflectance of metallized back plate of a solar cell and modest absorption in the bulk of the material for the near IR region of the spectrum permits one to measure in reflected light also the phase anisotropy distributions in final solar cell product. Based on the ideas implemented in the interferoscope a measuring system for tomographic imaging of volumetric and surface cracks in optical coatings, MEMS sensors and meta-material components made of plastic, glass and ceramics can be developed.

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7. REFERENCES

1. S. He, S. Danyluk, I. Tarasov, S. Ostapenko, Residual stresses in polycrystalline sheet silicon and it's relation to lifetime, Center for Microelectronics Research, University of South Florida (2005)